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Stimulated emission at 257 nm from optically-pumped AlGaN/AlN heterostructure on AlN substrate

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Optically pumped deep-ultraviolet lasers operating at room temperature are demonstrated from heterostructures consisting of $Al_xGa_{1-x}N/AlN$ grown on (0001) AlN substrate. The substantial reduction of the threading dislocation density by using a native AlN substrate over sapphire substrates is critical to the realization of the photo-pumped lasers. The threshold power density was 1.88 MW cm^{-2}. The layers below the active region were Si-doped and had bottom waveguide and cladding layer n-type structures required for diode lasers, thus demonstrating the feasibility of deep UV lasing for the proposed structures on AlN substrates by current injection, provided that effective hole injection layers are included.

1 Introduction Deep ultraviolet (DUV) optoelectronic devices operating at $\lambda < 280$ nm have recently come to the forefront of development for a number of applications including water purification, bio-agent detection, and optical memory storage [1, 2]. Traditionally, low-pressure mercury lamps have been used to produce UV emission at $\lambda = 254$ nm. However, a compact and high-power ultraviolet semiconductor device such as a superluminescent light emitting diode (SLED) or laser diode (LD) emitting in the germicidal region of the UV spectrum would be preferred as a more portable and less toxic alternative. The wide-bandgap III-nitride material system, specifically AlN and its composites: AlGaN and AlGaInN, can access the entire spectral range from near (320–400 nm) to middle (280–320 nm) and deep UV (200–280 nm) [3–8]. However, a number of difficulties arise as the aluminum (Al) mole fraction is increased to achieve a wider bandgap and shorter wavelength, such as higher crystalline defect densities and increased difficulty achieving effective doping. Thus, demonstration of semiconductor-based DUV lasers by current injection and optical pumping is quite rare – there has been no previous report of a DUV LD, to the best of our knowledge, and the reported quantum efficiencies for the optically pumped DUV heterostructures remain low.

III-nitride (III–N) materials have been typically grown via heteroepitaxy on foreign substrates such as sapphire or SiC, due to their relative availability and low cost. However, the differences in lattice constant and thermal expansion coefficient between substrates and epitaxial layers lead to the formation of threading dislocations during the thermal cycle as well as epitaxial growth, which are particularly severe for layers with higher Al content [9]. Dislocation reduction techniques such as inclusion of a low temperature nucleation layer, superlattices, and graded layers have been used to some degree of success in UV emitters, however high-efficiency emitters in the sub-300 nm range remain elusive, especially for LDs where a minimized defect density is critical to the realization of stimulated emission [10–12].

In this study, we have used a (0001) native AlN substrate, prepared from high-quality bulk crystal, to produce optically pumped DUV lasers. This allows us to grow a homoepitaxial AlN buffer layer, which significantly reduces the density of dislocations in the epitaxial structures. It also eliminates the differences in thermal expansion of materials, which limits crack formation during growth and subsequent cool down.

2 Experimental Prior to growth, the AlN substrates were prepared in a 3:1 H_2SO_4:H_3PO_4 solution at 90 °C to remove the native surface oxide [13]. An *in situ* high-temperature ammonia treatment was then used to further etch the oxide to enable smooth AlN homoepitaxial growth. The epitaxial structures were grown in a $6 \times 2''$ metalorganic chemical vapor deposition reactor with close-coupled showerhead, manufactured by Aixtron. Another difficulty encountered in the growth of high Al content structures is the low ad-atom mobility of Al atoms on the growing surface compared to Ga atoms. Thus, a high temperature and low V/III ratio must be carefully calibrated in order to promote smooth, two dimensional AlN and AlGaN layer growth [14, 15]. In this work, we have used a temperature of 1155 °C and low V/III ratio for the AlN buffer and all subsequent ternary layers. The ideal temperature range for such a structure could be above 1200 °C, however inherent limitations in the reactor design, particularly the tolerance level of the heater for the wafers and cooling systems for the chamber, prevent us from achieving such a high growth temperature.

The structure is essentially the lower half of a DUV LD designed specifically for optical pumping, but with further expansion into electrical injection with the addition of p-type layers in future structures. The structure began with a 200 nm homoepitaxial AlN buffer layer, followed by two strain-reducing superlattices consisting of 50 periods of $Al_{0.66}Ga_{0.34}N$/AlN (2 nm/2 nm) and 50 periods of $Al_{0.55}Ga_{0.45}N$/$Al_{0.66}Ga_{0.34}N$ (2 nm/2 nm). These are deemed necessary to provide a gradient of lattice constant between the AlN and the following rather thick and low-Al-content Si-doped $Al_{0.55}Ga_{0.45}N$ n-type (n-$Al_{0.55}Ga_{0.45}N$:Si) electron injection and contact layer. The Al composition of this layer is a crucial design aspect of a DUV LD, as it must be low enough to accommodate both efficient electron injection and ohmic contact, yet higher than that of the active region so as not to absorb emitted photons. Following the contact layer is a 300 nm-graded layer from $Al_{0.55}Ga_{0.45}N$ to $Al_{0.8}Ga_{0.2}N$, which acts as n-type cladding, enhancing the optical field of the active region, albeit at the expense of electron concentration in the multiple-quantum-well (MQWs). This trade-off must be carefully balanced, thus our decision to use composition grading to reduce the energy barrier created by a more abrupt conduction band discontinuity. The grading layers also serve to distribute the polarization charges present at heterointerfaces, subsequently reducing the barrier height for election injection. The $Al_{0.8}Ga_{0.2}N$ cladding is then linearly graded down over 435 nm to the composition of the quantum-well barrier (QWB), followed by a three-period $Al_{0.66}Ga_{0.34}N$/$Al_{0.53}Ga_{0.47}N$ (5 nm/2.8 nm) MQW active region. Finally, 12 nm of undoped $Al_{0.66}Ga_{0.34}N$ was used as a cap layer. Our structure specifically designed for optical pumping ends here, as to not inhibit the injection of photons to the active region with addition of thick p-type cladding and contact layers.

3 Results and discussion Figure 1 shows the asymmetric (105) reciprocal space mapping (RSM) of the epitaxial structure taken by high-resolution triple-axis X-ray diffractometer. Even with the wide compositional variation and thick layers, the RSM shows the entire structure is pseudomorphically grown on AlN substrate. Figure 2 is a cross-section of the structure taken with transmission electron microscopy with $g = (0002)$; an image of the same device grown on sapphire substrate with additional low-temperature buffer layer is also presented for comparison. Threading dislocations are readily seen in high density in the sapphire-based epitaxial structure sample; in contrast, the structure grown on AlN substrate exhibits a significantly lower occurrence of threading dislocations. This reduction in defect density, owing to a native AlN substrate and reduced strain state, is crucial to enabling stimulated emission for $\lambda < 300$ nm.

The epitaxial structure was thinned from the backside down to 50 μm via a chemical-mechanical lapping process and then cleaved into laser bars with a cavity length of 1 mm. The optical cavity forms along *m*-direction with cleaved facet mirrors on the *m*-planes.

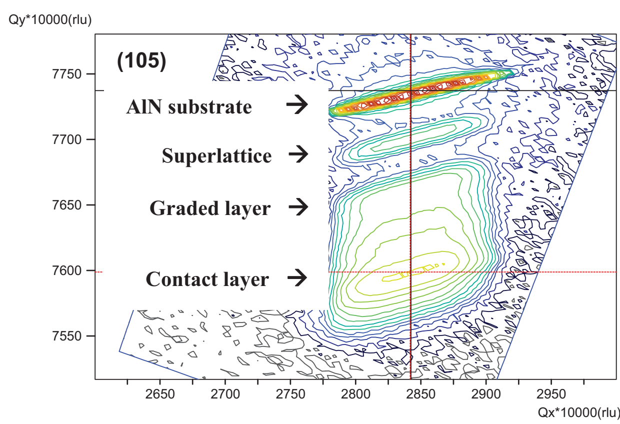

Figure 1 X-ray diffraction RSM of the epitaxial structure on an AlN substrate demonstrating pseudomorphic growth.

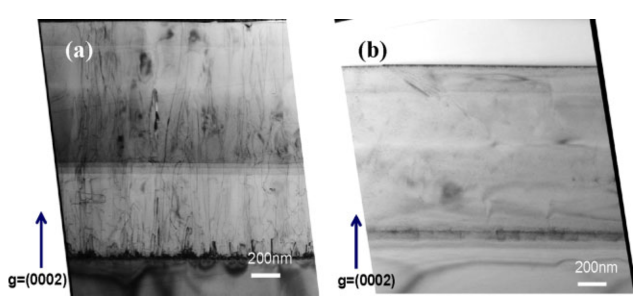

Figure 2 Cross-sectional image of identical structures on (a) sapphire and (b) an AlN substrate, taken by transmission electron microscopy.

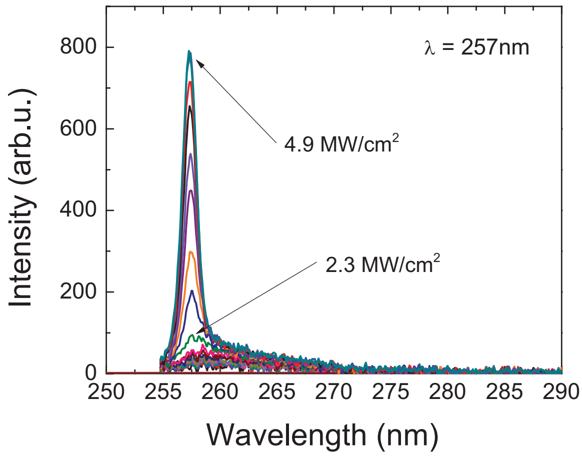

Figure 3 Emission spectra at various excitation densities demonstrating lasing at $\lambda \sim 257$ nm.

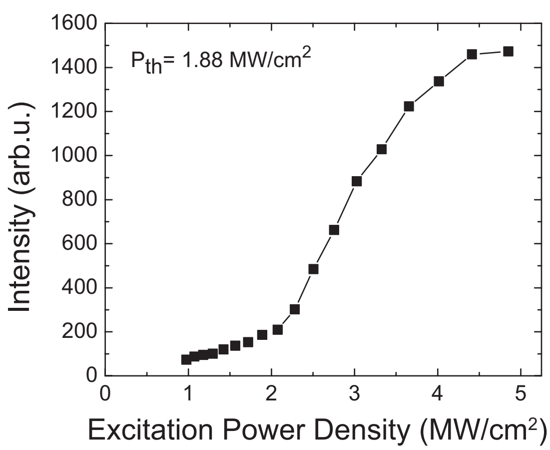

Figure 4 Optical output intensity as a function of excitation power density (*L–L* curve).

The laser bars were optically pumped with a 248 nm KrF excimer laser with 20 mW maximum power. The sample emission spectrum is shown in Fig. 3, lasing at a wavelength of 257 nm with measured full-width at half maximum (FWHM) of <2 nm. The maximum excitation power density is 4.9 MW cm^{-2}. Figure 4 shows the optical output power as a function of excitation density (light output–excitation light, *L–L* curve), demonstrating lasing with a pump power threshold density of 1.88 MW cm^{-2}. While this is higher than threshold power densities reported elsewhere (e.g. Wunderer et al. in Ref. [7]), it is to be expected at shorter wavelengths in higher Al content structures. We believe this threshold power density can be significantly reduced with further optimization of the layer structure, specifically the cladding layers, to improve optical confinement such that the optical gain profile lies more squarely within the active region, and further optimization of materials.

4 Conclusions In summary, we have grown and fabricated a DUV laser on an AlN substrate and demonstrated laser operation via optical pumping. The epitaxial design includes a full n-type Si-doped cladding layer for a future expansion into a full LD design with electrical injection anticipated. The development of high conductivity, high Al containing p-type $Al_xGa_{1-x}N$ will be crucial to this venture, and it is critical to have an appropriate active region capable of lasing as demonstrated herein.

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